

Interactive Job-Shop Scheduling: How to combine Operations Research Heuristics with Human Abilities

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Summary: The aim of the paper is to demonstrate the need for interactive human-computer scheduling. The process of solving most scheduling problems involves ignoring information on two occasions. Firstly in the modelling of the problem as an optimising system, and secondly in the application of a heuristic to approximately solve that system. The second step is generally necessary because most scheduling problems are NP-hard. Hence the solution is often based on assumptions that make the problem divorced from the one the scheduler faces in the actual manufacturing environment. OR heuristics cannot handle the range of contingencies that arise. In the majority of job shops scheduling is left to humans. The authors see interactive scheduling as a means to extend human abilities and to apply scheduling heuristics to realistic scheduling problems. We will discuss how to bound the problem to apply available OR heuristics.

1. INTRODUCTION

Decades of operations research (OR) have had little impact on the scheduling practices of small-batch manufacturing industries. The more recent foray by the artificial intelligence (AI) community into the art of scheduling has not brought with it greater industrial support. A fresh approach may be more profitable. Many aspects of scheduling jobs within a plant are understood best by humans working in the particular environment. Within the context of local knowledge, they know how to handle information that may be diverse, inexact, or conflicting. Instead of focussing on mathematical techniques, the problem's locus should move to the needs of persons who have to take responsibility for the planning of production. In this paper the reasons for this approach are discussed, and the characteristics of a Decision Support System that can support collaborative decision-making between intelligent human and computer agents are explored.

2. JOB-SHOP SCHEDULING

2.1 Operations Research

Scheduling is notoriously difficult. After some early successes in the 1950s and 60s, such as Johnson's algorithm for sequencing n jobs on two machines, it was found that even the simplest idealised problems, whilst they may be able to be formulated elegantly using integer or dynamic programming require an inordinate amount of computation time to solve exactly. The development of the theory of computational complexity has greatly clarified the issue. We can now say that the vast majority of scheduling problems require some sort of combinatorial optimisation and so are generally NP-hard. That is, for these problems the fastest currently available algorithms (exact solution methods) are exponential time. In other words, the number of computations required to solve the model exactly grows exponentially with the problem size, for example the number of jobs to be

scheduled. Indeed, it has been estimated that about 90% of scheduling problems are NP-hard. So the curse of dimensionality remains and forces us to search for heuristics, that is fast (polynomial time) procedures which are near optimal in some sense.

A heuristic has been defined as 'a method which on the basis of experience or judgment, seems likely to yield a good solution to a problem, but which cannot be guaranteed to produce an optimum' (1). Bartholdi and Platzman (2) remarked that 'a heuristic may be viewed as an information processor that deliberately but judiciously ignores certain information... the art of heuristic design lies in knowing exactly what information to ignore.' The difficulty with applying heuristics to scheduling problems is that it is very difficult to decide which information to ignore. The loss of information takes place in two stages. Firstly in order to build an operations research model we need to ignore some aspects of the real problem. For example, we may assume that set-up times are predictable, or that the goal is simple profit maximisation and is not affected by any hidden agendas. Secondly, once the model has been formulated we remove it even further from reality by using a heuristic which may ignore further information. For example, in many problems we use a 'greedy' (or myopic) type of heuristic which, essentially, looks only one step ahead. It has the advantage of being very easy to implement but by its very nature it ignores everything that happens after the first step.

In commenting on this state of affairs, McKay, Safayeni and Buzacott (3) saw that 'The problem definition is so far removed from job-shop reality that perhaps a different name for the research should be considered'. They queried the relevance of its theoretical formulation: a formulation in which the underlying assumptions and structure have remained virtually unchanged for 30 years. Their opinion comes from surveying 40 schedulers and conducting four, informal and explorative, case-studies. They found the concerns and needs of practising schedulers differed from the theoretical concerns of OR researchers. Over a series of job-shop scheduling seminars, of which more than 200 schedulers participated, they affirmed that some of these concerns and needs were widespread.

The theoretical formulation of the job-shop scheduling problem in classical OR research does not address many needs and concerns of practising schedulers. Schedulers have to satisfy many stated and unstated conflicting goals, using hard and soft information that is possibly incomplete, ambiguous, biased, outdated, and erroneous. Using intuition, they fill in the blanks about what is happening, and, what can and what will happen, on the floor. This includes sensory data and a mental model of the situation. What they need to ponder upon varies: 'When scheduling, some issues will be paramount while others will be ignored. These subsets will change with time, date, mood, climate, and so forth. Any issue can at sometime affect the scheduling decision' (3).

There are various ways for schedulers to deal with variability and constraints. Constraints do not have to remain as they were set; schedulers may alter the short-term physical make up of the shop, or, the short-term processing logic. Also, for at least a short term, if not for the long term, they can often change the shop's capacity.

In many manufacturing environments unplanned events dominate. This is especially so where there is a multitude of small-batches. McKay *et al.* (3) found that typically a shop is seldom stable for longer than half an hour. Something is always happening unexpectedly: the effects of which normally last longer than the batch processing time for the work in process in the area affected. There are many constraints or issues that can affect the scheduling. They may arise at different times and for different reasons. Before jobs already in the system have progressed through the queues, new jobs may arrive; their arrival may make the previously planned order of jobs in the queues irrelevant. In practice, it may be impracticable to alter the place of some jobs in a queue. Often those jobs, for whom processing is imminent, have placed calls on resources and materials that may not readily be reversed. Changes may be restrained to limit chaos and confusion at the shop floor due to chopping and changing the order of work. Under these circumstances, if all jobs in the queue are not available for revision, the *raison d'être* for applying a particular heuristic becomes questionable.

One of the authors found, at a fan-fold form printing company, the minimisation of the set-

up time was a principal factor affecting the schedule (4). Reducing the set-up time, when there was a queue of waiting jobs, increased the availability of the printing presses. The person, who has the responsibility for scheduling, attempts to minimise the set-up time by arranging the jobs. Changes to one of the parameters have a major effect on set-up time. Often-occurring changes to three other parameters have a minor effect on set-up time (Of the ten parameters that may influence the set-up only a few frequently occur). Recently some papers on scheduling of jobs on single (5,6) and parallel machines with set-ups have appeared in the literature (7, 8, 9 and 10). While advancing the understanding of this class of problem, they still deal with problems that are far simpler than this case-study.

The scheduler's strategy is more complex than merely ordering jobs to minimise set-up time. In deciding a schedule, he deliberates upon other aspects of the job and the environment. His goal is composite. It includes, but not solely, the maximisation of machine utilisation and the minimisation of tardiness. This part of the goal can be expressed in a quantifiable form by relatively weighting these objectives in a linear function. But, in practice the scheduler does not use a linear function, nor any similar expressions. More on that later. Part of his goal is to satisfy the customer. This is difficult to express explicitly. Customers are satisfied in various ways. For some customers the meeting of the date agreed upon is most important. For others, their primary interest is for the turnaround to be fast. While yet again, other customers are more concerned about the quality of the job, which both machine allocation and processing-speed affect.

2.2 Artificial Intelligence

The raising of these issues brings us around to the AI approach to scheduling. In recent years, the AI community has also tackled the scheduling problem. Their solutions reside in constraint-based reasoning. AI techniques extend the limited horizon of OR heuristics. They can react to the shop's current state. While the OR approach disregards all but a few quantitative indicators, AI can incorporate diffuse factors, which may be both quantitative and qualitative. Schedule construction is cast as a constraint-directed activity that seeks feasible schedules that

satisfy the constraints placed on jobs and machines. In optimising the schedule, they can put all relevant scheduling knowledge to use (11). Their proponents claim that, in response to the actual current state of the factory, their systems construct schedules, which are accurate and timely. They therefore go beyond a few quantifiable measures, as occurs with the OR approach. In the printing-company example, the factors used in deciding the order of jobs to minimise set-up time could be expressed as rules that suit constraint satisfaction.

For a constraint-based scheduler to act effectively, all factors that are important in setting the schedule have to be heeded. Alas, this is also the root of an important shortcoming. To fully automate scheduling, the system has to cater for all circumstances that could ever arise. Many factors may have to be thought about: some of these are, the presence of multiple resources and multiple routings, operation precedence, job priorities, random failures, availability of material, changes in production goals, and the call to expedite some jobs. While these factors probably can be placed in a rule base, the cost for their capture is usually high. Companies are reluctant to expend enough time and money on creating bases that are large enough to make well-formed decisions.

There is also a perverse negative to having well-developed rule-bases. Rule bases that are extensive exhibit brittleness. Even if a rule base is large enough, what happens when the environment changes? Resources may change. Products may change. Unforeseen methods or materials may be introduced. These are but some possible changes. What then happens to the rule base? Is it upgraded? Are the changes ignored and its advice accepted? Is the schedule used only after whosoever holds responsibility has vigilantly made the necessary modifications? Factors that may result in quite divergent scheduling outcomes have often to be reconciled when a schedule is developed. How can this be done?

While AI researchers have extended the parameters of interest beyond those of OR, in essence the problem formulation does not differ (3). In investigating how to apply AI to the computational-complexity problem, they use the same limitations and assumptions as is used in OR.

3. INTERACTIVE SCHEDULING

Humans can bring to the decision-making process special competencies pertinent to scheduling (12). While the predetermined logic structure of computers may cause them difficulty in managing unplanned events, such as machine breakdowns and changes in priorities, humans are able to handle unexpected events and to formulate general rules from specific cases (13, 14). Humans can apply inductive logic to get beyond the imperative for computers to have all pertinent knowledge articulated *a priori*. While computers can manipulate large amounts of data and to automate procedural steps, when the number of conceivable states of a discrete-parts manufacturing system is large, an automated system may be unable to cope with all the combinations it has to search. In other words, even if the activities and events in a manufacturing system may occur in a deterministic way, they may be too complex for functional analysis (15). On the other hand, humans may find such situations quite simple to manage. By using their abilities to use inductive logic and to readily recognise patterns in the data and identify what is, and what is not, essential, they can narrow the search space (13). By intervening so, the number of constraints that the computer has to manipulate is reduced (16).

Even where there has been a reduction in the search space, the computer may still be too slow to meet the dynamics of the system. There may be changes to routings, configurations, operation precedence, and job priorities, availability of material, and production goals; Machines may fail; Jobs may need to be expedited. Where computer systems are incapable of responding rapidly enough, humans may have to identify the system's state, decide upon the course of action, and then carry it out (17, 18, 19, 20).

The form that interactive scheduling may take is wide ranging. At one extreme, the human acts as the principal controller, taking advice from the computer. At the opposite bound, the principal controller is the computer with the human's role limited to performing corrections and adjustments (16). The computer agent builds a schedule. Then, the human agent makes modifications. This process iterates until a satisfactory schedule is built. The computer often applies a single indicator of performance to measure the level

of satisfaction. This interaction is essentially passive. During the execution cycle, each agent takes its turn, without any interchange with the other. Generally, users are free to alter Gantt charts produced by the computer, as long as they do not violate constraints (e.g. operation precedence). The order of jobs in a queue may be rearranged. Jobs may be reallocated from one resource to another. Generally, changes are made by directly manipulating objects on the screen. Once done, a "rebuild" algorithm reschedules the activities that temporally follow the changes.

With interactive systems, users should be able:

1. to build schedules by methods that they use naturally, but are hard to represent as algorithms;
2. to pursue goals and enforce constraints that cannot, or have not been given, an accurate computational representation; and
3. to form schedules for rapidly changing production environments.

Significant research into interactive scheduling has been conducted at Purdue University (20, 21, 22, 23). Studies have compared the performance of humans, combinations of automated simple priority rules, and human selection of a preferred schedule from a number produced automatically by different priority rules. Minimisation of the maximum and average tardiness and the maximisation of machine utilisation were used as scheduling goals. These studies concluded that an important part of human decision-making is concerned with predicting future system states (20).

At Georgia Institute of Technology, the emphasis has been on the human operator's manual and cognitive actions. Using a real-time simulator of an FMS (Georgia Tech-FMS), humans sought to improve system performance by meeting due date while simultaneously minimising inventory (25, 26). The human supervisors of the cell were regarded as systems managers, who focussed on the long-term goals. They were provided with the means to modify the scheduling heuristic and expedite jobs. They could vary the value of the weighting factor, a , in the scheduling heuristic, a Weighted Operation Priority Index (WOPI) that is a linear combination of SPT and EDD ($WOPI = a \text{ SPT} + (1 - a) \text{ EDD}$). Under experimental conditions, subjects were found to base their decisions on current, detailed, system-status information, and not

on performance history, as the researchers expected. The researchers inferred that decisions by systems managers, who only intervene under alarm conditions, may lack the insight obtained from tracking of system sensitivity and from applying intricate knowledge of the system state.

In interactive scheduling, humans participate in schedule construction. They do not merely respond to choices proposed by the computer, as is the norm with interactive systems. The computer's responses need to reflect the user's internalised model of the scheduling problem, so that the human-computer interaction suits the information-processing capacity and style of the operator (27). An interactive scheduling system draws upon the special competencies that humans bring to the scheduling activity. Therefore its creation depends upon understanding how humans go about scheduling.

Leaving a wide margin of action to humans ensures that they maintain a sufficiently well-developed mental model for them to exercise initiative. By being actively involved in schedule construction, humans can react to critical system events. The user, using the computer acting as a tool, can connect his/her own intention, or action, and the effects it produces. The computer's functions and behaviour are completely transparent, and its reactions are self-explanatory and adapted to the actual working situation (28). This tool provides a means for representing parameters related to scheduling; the context, objects, agents, and activities that interplay in devising a schedule (29).

Instead of merely cursorily scanning schedules as presented, the interactive scheduler compels users to examine the underlying properties in establishing and maintaining them. The use of the interactive scheduler occupies a significant portion of the users' attention and abilities (16). This places users in a position where they keep, and hone, their skills, particularly those relating to inductive logic and pattern-recognition (12).

4. COGNITIVE TOOLS

For a Decision support System (DSS) to act as a tool, it must be able to be wielded by humans, under their cognitive control, so as to achieve their desired objectives (30). To be instrumental, it should have the following capabilities:

1. The computer's knowledge about the state of the system, viable hypotheses, and diagnostic directions is available to the human (19).
2. Humans should have the wherewithal for controlling the computer's reasoning. This includes mechanisms for the human problem-solver to add to or to change the information or knowledge that the computer is using about the state of the system.

Norman (31) delineates three critical components of an artifact, or tool: their role in enhancing cognition; the degrees of engagement that one can experience; and the roles of representational format. Artifacts act as mediators between the users and the world, both in execution and in perception. From Norman's perspective, an interactive scheduler is a representational system having the following elements:

- The represented world — the manufacturing environment;
- The representing world — a set of symbols;
- An interpreter (which includes procedures for operating upon the representation).

Jobs and resources are represented as symbolic objects. The choice of representation and the nomination of interactions permitted by the artifact affect the interaction of the human scheduler with these objects (32, 33, 34). Each representation has its own set of constraints and intrinsic and extrinsic properties. It emphasises some mappings at the expense of others. Some mappings are explicit and visible, while others are neglected. The physical depiction portrayed by the representation suggests and reminds the user of the set of possible operations (31).

As a tool the interactive scheduler equips humans with a means for them to exercise their understanding of the scheduling process, which they have developed within the represented world. For the tool to be useable, the surface representation displayed on the screen must correspond to something that is interpretable by human schedulers. In creating or changing a schedule, schedulers need to move freely within the decision space (see the discussion on decision making above): seeking patterns within data, recognising familiar work situations, and to exploring decision-making strategies under novel circumstances. The interface therefore needs to transform the artifact's representational system (a world of heuristics, constraints, and

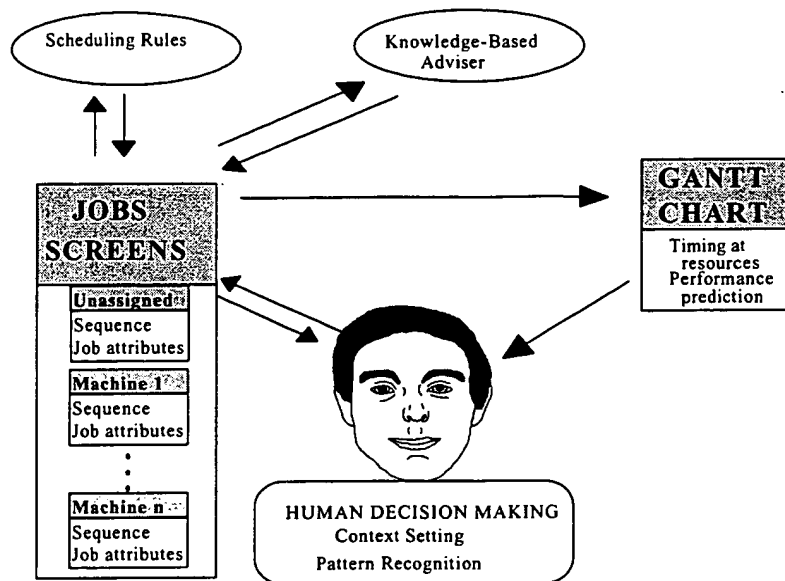


Figure 1 Interface elements and their location in a hybrid intelligent scheduling system

algorithmic calculation) to those that match the properties of the person (31). Norman vests the interpreter with this role.

The format of the display is a salient feature of an interactive scheduler. Properties are displayed in a form that allows for cognitive congruence between the methods pursued by the human and the computer. The syntax of the display must not obscure the data (35).

5. THE PROTOTYPE INTERACTIVE SCHEDULER

The structure of the prototype interactive scheduler is shown in figure 1. The human scheduler interacts with the computing system through two graphical windows, the Jobs Screen and the Gantt Chart. The human is an active participant in the decision-making process leading to the production of a Gantt chart. Therefore, the major interactive decision-making activity occurs using the Jobs Screen.

In the prototype interactive scheduler, jobs are represented by symbolic objects. These objects display, on the screen, features that the human may need to use in constructing a schedule. The human scheduler arranges these objects in the order that he/she will submit them to a resource. Figure 2 shows a simplified version of the "Jobs Screen" for a single resource. The form of the display conforms to Norman's additive and substitutive scales. An additive scale makes it easy for the human scheduler to

compare processing times by scanning vertically. While additive scales generally suit size comparison, for cases requiring an exact numerical value, Arabic notation is clearly superior. For our example, arranging jobs so that width decreases between jobs saves time in setting up. In seeking a job to follow one with a width of 229 mm, the scheduler would scan the width of other jobs. If the scale was additive, the scheduler would find difficulty in deciding whether a width was 228 mm, which would incur no set-up penalty, or 230 mm, which would do so. Therefore, the object displays width in Arabic notation, a substitutive scale. A graphic links the widths of jobs in which the widths increase to draw attention to situations incurring a corresponding set-up cost.

Substitutive scales befit the display of depth of printed form and colour. For the printing cylinder, horizontal location of the bar indicates its size, and the bar's height expresses the depth as a fraction of the cylinder's size; for example, a form of 5.25 inch depth would appear as a half height bar on a 11-inch cylinder. By showing the depth in this way, the scheduler can see when a change in depth occurs, whether the cylinder size needs changing requiring a major set-up, or only a perforating tool needs to be added or removed, which is but a minor set-up. For colours, the location of bars horizontally relates to commonly-occurring colours. To print the same colour on the front and back of a form

requires two modules. Where this occurs, the bar has twice the height.

The judicious use of additive and substitutive scales in displaying job data helps the human scheduler to observe many features across all jobs. He/she may immediately act exercising skill-based behaviour. Where the scheduler sees patterns that fit his/her well-rehearsed heuristics, he/she may apply rule-based behaviour to allocate jobs to resources and to arrange the order of processing. The procedural steps to carry out these heuristics may be automated; The shaded area on right identifies where in the decision space the computer offers support. Often the scheduler needs to choose between different heuristics (see the discussion on the printing example under the sections on Operations Research). Having ordered the jobs on the Jobs Screen according to the competing heuristics, the Gantt chart shows the timing of jobs at each resource and predicted performance measures (percentage machine utilisation and percentage of tardy jobs) both at resource and global levels.

resource the order of processing is also a conjoint decision. By being actively involved before a Gantt chart has been built, the human can deal with contingencies and other aspects of scheduling jobs that are difficult to vest in a computer decision-maker. The use of intelligent human decision makers with vast local knowledge also obviates the need for an exhaustive knowledge base.

The interactive approach to scheduling can help to invigorate Operations Research, as heuristics, whose applicability has been under question, may become quite useful when applied at a higher level. The human can act as an intermediary between the real-world manufacturing environment and the abstract world of operations research, by:

- dealing with the stated and unstated conflicting goals,
- resolving how to use information that is incomplete, ambiguous, biased, outdated, or erroneous, and,
- grouping jobs to meet the specific criteria for applying selected heuristics.

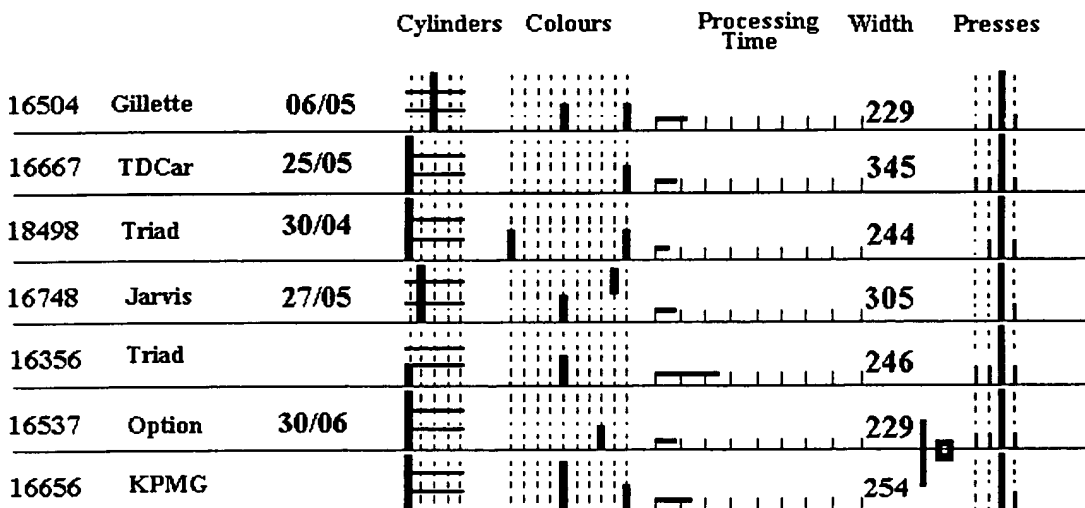


Figure 2 Jobs Screen for Press 3: Jobs and their characteristics
A partial display of objects representing job attributes

Much could be said about the design of displays; Indeed, far too much for this overview of interactive scheduling to describe adequately, let alone to mount a discussion. Therefore, it must be left for another occasion.

6. CONCLUSION

In an interactive scheduling system, a human and a computer act together to decide which jobs are allocated to which resources. For each

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RESEARCH HEURISTICS WITH HUMAN ABILITIES**
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KEYWORDS: Scheduling, interactive, human-computer

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